

INITIAL OPERATION, MODELING AND OPTIMIZATION OF A LOW-VELOCITY AUGMENTED RAILGUN*

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Abstract

An electromagnetic launcher is being studied for ejection of 350-g projectiles at velocities of up to 140 m/s. The electromagnetic approach is desirable because of the variable ejection velocity, high payload fraction, and lack of pyrotechnics. The low velocity of the projectile allows the use of low-voltage, solid-state switching in the pulsed power, but makes obtaining high-efficiency more difficult.

The launcher is a 4.5-cm square bore, 80-cm long fully augmented system, with copper inner rails and aluminum augmenting rails. The launcher is driven by 2, 5000 μ F, 5 kV capacitor banks, with a thyristor switch and diode crowbar for each bank. The banks are connected to the launcher with copper buswork. The diagnostics include the current in each bank, B-dot probes for the position of the projectile, a laser time-of-flight velocity measurement at the muzzle and the armature voltage, measured from the muzzle. The armature voltage measurement requires substantial corrections to remove the induced voltages from the augmenting and armature fields.

The projectile is a Delrin body with aluminum alloy 1100 wires as the armature. Six to ten, 0.32-cm diameter wires are used. The wires run through the projectile in separate holes, then are bent into a staple shape in grooves along the sides of the projectile. The wires are then sanded to obtain a flat surface for contact to the rails. The $\mathbf{J} \times \mathbf{B}$ forces that propel the projectile forward also force the wire sides into the rails to maintain good electrical contact.

The design goals of 350-g and 140 m/s are achieved, but at an overall electrical efficiency of only 7%. The electrical parameters of the various circuit elements are measured, and the early-time skin resistances of several elements lead to the low efficiency. Reconfiguring these elements to have lower early time resistance is predicted to improve the efficiency to the 15% range. Results of circuit measurements and models will be presented.

I. INTRODUCTION

Most recent railgun research has concentrated on achieving high velocity operation, in excess of 2 km/s, with solid armatures. Issues have been avoiding gouging, maintaining low voltage contact throughout the acceleration process, and increasing the energy efficiency to minimize the needed power supply. The contact phenomenon between armature and rail has been investigated to lower the contact resistive energy loss and the erosion of rail surface. [1]-[4]

In this study, a solid armature railgun is used to accelerate projectiles to low velocity. The desired performance is a velocity of 140m/sec with a 350g projectile. Other important goals are to get high efficiency, 15-20%, and to reduce the erosion of rail surface to allow multiple shot operation. It is difficult to increase the efficiency of a low velocity railgun because the resistive energy loss is increased while armature moves slowly.

II. EXPERIMENTAL SETUP

A railgun experiment has been fabricated. The launcher has an augmented rail to reduce the current amplitude while maintaining the electromagnetic force. The railgun setup is shown in Fig. 1.



Figure 1. The railgun setup.

A. Power Supply

The railgun setup has two identical capacitor banks. Two capacitor banks are usually triggered simultaneously. Each capacitor bank has 5 mF, consisting of 4 Aerovox

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14. ABSTRACT An electromagnetic launcher is being studied for ejection of 350-g projectiles at velocities of up to 140 m/s. The electromagnetic approach is desirable because of the variable ejection velocity, high payload fraction, and lack of pyrotechnics. The low velocity of the projectile allows the use of low-voltage, solid-state switching in the pulsed power, but makes obtaining high-efficiency more difficult. The launcher is a 4.5-cm square bore, 80-cm long fully augmented system, with copper inner rails and aluminum augmenting rails. The launcher is driven by 2, 5000 iF, 5 kV capacitor banks, with a thyristor switch and diode crowbar for each bank. The banks are connected to the launcher with copper buswork. The diagnostics include the current in each bank, B-dot probes for the position of the projectile, a laser time-of-flight velocity measurement at the muzzle and the armature voltage, measured from the muzzle. The armature voltage measurement requires substantial corrections to remove the induced voltages from the augmenting and armature fields. The projectile is a Delrin body with aluminum alloy 1100 wires as the armature. Six to ten, 0.32-cm diameter wires are used. The wires run through the projectile in separate holes, then are bent into a staple shape in grooves along the sides of the projectile. The wires are then sanded to obtain a flat surface for contact to the rails. The JxB forces that propel the projectile forward also force the wire sides into the rails to maintain good electrical contact.		
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capacitors. The maximum energy of a capacitor bank is 62.5kJ at 5kV. A capacitor bank has a 125mm thyristor as the main switch, SPCO XSPT411A, and a 100mm diode for crowbarring, SPCO SDD303KT. A snubber R-C circuit, 0.25Ω-5uF, is installed in parallel to the thyristor. Belleville springs are used to preload the thyristor and diode with 111~133kN and 75~85kN, respectively. The buswork at the thyristor, diode, and feed to the barrel consists of copper 110 plate(12.5 mm T×100 mm W).

B. Launcher

Launcher has a 0.8m long augmented rail to reduce the current amplitude while maintaining the electromagnetic force. The resistive loss of solid armature contact and erosion of rail surface can be reduced by lowering the amplitude of armature current. The bore is 45×45mm square. The length of inner rail is 0.86m long and the cross section 50mm×25mm of alloy 110 copper. The augmented rail of aluminum wraps the inner rail. The surface of the augmented rail is grooved to reduce the resistance of rail by increasing the effective area of skin effect. The insulator of bore is G-10 fiberglass. A thin Kapton film is used for insulation between inner and augmented rails.

C. Armature and projectile

The armature shown Fig. 2 is composed of ten, 32-mm dia. wires of aluminum-1100. These wires pass through the projectile of 45mm thickness in parallel, separated from each other by the Delrin to assure current sharing between the individual wires and to support the wires against the compression forces during acceleration. The 15mm long ends of each wire are flat and contact the inner rails. The aluminum armature wires can also serve as a lubricant between armature and rail because the melting temperature of aluminum is lower than that of copper. As the result, the erosion of rail can be reduced.



Figure 2. Armature and Projectile.

D. Diagnostics

Diagnostics are on a PC-based acquisition system, with CAMAC digitizers. The B-dot probes are isolated from the railgun setup, and are connected to differential mode amplifiers through shielded twisted-pair cables. Stand-alone oscilloscopes are used to make direct voltage measurement. The oscilloscopes are powered by battery to float them from ground and installed in the steel shield-box to remove the effect of magnetic field by the high current of railgun. The signals are obtained as Table 1.

Table 1. Diagnostic measurement.

Measurement	Sensor type	Num.
Switch or crowbar-diode current	B-dot probe	1
Current of a capacitor bank or total current	B-dot probe or Rogowski Coil	2
In-bore armature position	B-dot probe	4
Muzzle velocity	Laser time-of-flight	1
Muzzle or breech voltage	Voltage divider	1

III. EXPERIMENT RESULTS

A number of experiments were conducted: for testing and calibrating diagnostics, determining the parameters of various circuit elements, and accelerating projectiles to the design goal of 350g and 140m/sec.

The parameters of the railgun circuit are shown as Table 2. There are two kinds of parameters. One is the present measured value and the other is the new practical values which is being changed for improvement. There are also two values for the resistance, one before crowbarring and the other after. The values are determined by comparing the results of experiments to those of Pspice simulations. The di/dt of current is diminished after crowbarring period and the skin depth is increased according to current penetration time like Eq. (1). As the result, the resistance of each part is exponentially diminished to around 15% of the early time value. The resistance of each part except armature has nearly DC resistance 2~3msec after crowbarring.[2]

$$\delta(t) = 2\sqrt{\frac{t}{\pi\sigma\mu}} \quad (1)$$

where, $\delta(t)$ is skin depth, σ conductivity, and μ permeability, respectively.

Table 2. The present and improved parameters of the railgun setup.

Parameters	Present	Improved
Capacitor bank		
- capacitance	5 mF	5 mF
- Internal Inductance	0.25 μH	0.13 μH
- Internal Resistance	1.5 mΩ	0.9 mΩ
Buswork		
- Inductance	0.23 μH	0.7 μH
- Resistance *	196/26 μΩ	98/13 μΩ
Breech parts		
- Inductance	0.12 μH	0.12 μH
- Resistance *	240/38 μΩ	80/20 μΩ
Inner and augmented rails		
- Inductance gradient of inner rail	0.4 μH/m	0.4 μH/m
- Mutual Inductance gradient between inner rail and augmented rail	0.39 μH/m	0.39 μH/m
- Mutual Inductance of armature current to muzzle voltage	0.025μH	0.025μH
- Resistance of augmented rails *	580/92 μΩ	400/65 μΩ
- Resistance of inner rail *	536/71 μΩ	536/71 μΩ

* Resistance : before/after the end of crowbarring period

Armature resistance is calculated from the armature voltage determined by measuring muzzle voltage of the

inner rails. The muzzle voltage equation has four terms Eq. (2). [5]

$$V_{muz} = V_{arm} + M' v i + M' (x - l_{in}) \frac{di}{dt} + M_{arm} \frac{di}{dt} \quad (2)$$

where, V_{muz} is muzzle voltage, V_{arm} armature voltage, v projectile velocity, i current, x the position of projectile from breech, l_{in} the length of inner rail, M' mutual inductance gradient between augmented and inner rails, and M_{arm} Mutual Inductance of armature current to muzzle voltage, respectively.

Armature resistance and muzzle voltage, armature voltage, and armature current are shown in Fig. 3. Armature resistance increases up to about $600\mu\Omega$ during the rising time of current, $120\mu\text{sec}$. After that, it decreases and changes according to the condition of contact between armature and rails.

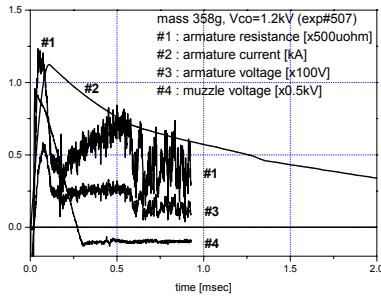


Figure 3. Armature resistance, muzzle voltage, armature voltage and armature current.

A projectile of 360g is launched up to 117m/sec with the energy efficiency of 6.7%. Fig. 4 shows the current shape. The rising time of current is about $120\mu\text{sec}$ and the in-bore travel time of projectile is 8.5msec. The peak of current is 242kA. The near term goal of this project is to improve the efficiency to 15~20%.

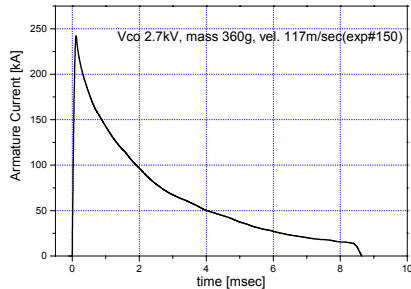


Figure 4. The experimental current, 360g at 120m/sec.

IV. COMPUTATIONS AND SIMULATION

The Lorentz propelling force of the augmented railgun is given by Eq. (3). [1][3]

$$F = \frac{1}{2} L_e' i^2 = \frac{1}{2} (L' + 2M') i^2 \quad (3)$$

where, F is magnetic force, L_e' effective inductance gradient of launcher, L' inductance gradient of inner rails, respectively.

The energy consumption of railgun is essentially partitioned to the kinetic energy of projectile and the heat loss of circuit resistance. Therefore, the relation of them, $Ratio_{loss}$, can be shown with the velocity of projectile and the total resistance of circuit as Eq. (4). This equation can be simplified when the resistance is supposed to be constant. From Eq. (4), it is found that the efficiency is determined by the mutual inductance gradient and the total resistance of the circuit at the specified velocity. It is needed to maximize the effective inductance gradient and minimize the resistance to get high efficiency.

$$Ratio_{loss} = \frac{\frac{1}{2} m v^2}{\int R i^2 dt} = \frac{L_e' v}{4 R} \quad (4)$$

where, $Ratio_{loss}$ is the ratio between kinetic and resistive energy, R the total resistance of railgun, and m the mass of projectile, respectively.

In reality, the resistance of circuit is not constant because skin depth and armature arc are changing. The time-varying resistance must be considered to analyze the energy consumption in detail. The power of railgun, $p(t)$, can be given as Eq. (5). The equation has two terms. One is a resonant term and the other is a consumption term.

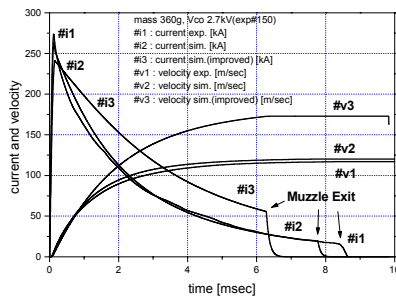
$$p(t) = \left(\frac{1}{C} \int i dt + L_{tot} \frac{di}{dt} \right) i + (R + L_e' v) i^2 \quad (5)$$

In a consumption term, the mass moving term, $L_e' v$, is like the resistance of electric circuit. And, it is changed by the velocity of projectile. In this study, the value of $L_e' v$ is always below $160\mu\Omega$, which is the value at $1.2\mu\text{H/m}$ and 140m/sec of the goal. In the early period of shot before the end of crowbarring period, the velocity is nearly zero but the resistance of circuit has the highest values, above $2.5\text{m}\Omega$ because of skin effect and the initial arc of armature. And, though it is reduced to about $200\sim 300\mu\Omega$ in the late period, it is still higher than $L_e' v$.

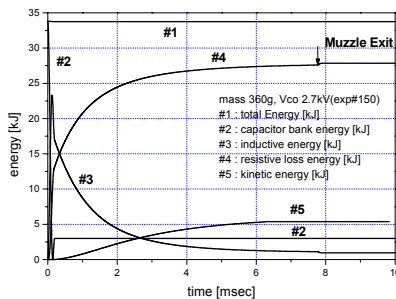
As shown at Eq. (5), it is needed to maximize the effective inductance gradient and also minimize the resistance to improve the efficiency. Efficiency improvements will come from reducing the early-time skin resistance, and tuning the inductance of the feeds to limit the skin current losses. For this, the values of L_{tot}

can be decided to reduce the resistive loss while limiting the residual inductive energy at projectile exit.

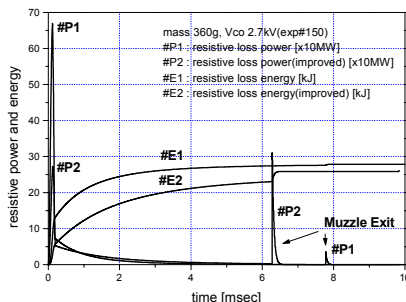
The railgun setup is modeled with Pspice. Pspice is used to develop new models and analyze the performance of electric circuit in detail. This Pspice code includes models of all parts of railgun setup. One of models is the time-varying inductor which represents the inductance variation of launcher and the energy transfer from electric energy to kinetic energy according to the movement of projectile. Another is the time-varying resistor which can consider the skin effect, armature arc, and movement of projectile. This code is used for the prediction of railgun and the analysis of experiment together. Fig. 5 shows the results of simulation and experiment.



(a) The simulation and experiment results of armature current and projectile velocity.



(b) The simulation results of energy distribution during shot.



(c) The simulation results of resistive energy and its power with the present and improved parameters.

Figure 5. The results of simulation and experiment at charging voltage 2.7kV, 360g projectile.

Fig. 5(a) shows the simulation and experiment results of armature current and projectile velocity. #i1, #i2, #v1, and #v2 show the validity of the developed Pspice code. The muzzle velocities are 117 and 120m/sec, respectively. #i3 and #v3 show the results with the improved parameters of Table 2. The velocity is improved up to 173m/sec. The residual amount of inductive energy at muzzle exit is increased according to the projectile velocity at the specified length of launcher.

Fig. 5(b) shows the simulation results of energy distribution during shot. It is found that about 45% of total energy is consumed at the resistance of circuit in early time, before the end of the crowbar period. It is needed to reduce the resistance and the current amplitude of the early time for the improvement of efficiency.

Fig. 5(c) shows the simulation results of resistive power and energy during shot. #P1, #E1 are the resistive power and energy of present parameters of Table 2. #P2, #E2 are those of the improved parameters. The resistances of parts are reduced to about 50~70%, through effective increased cross-section and surface area. An additional inductance of $0.47\mu\text{H}$ is added to the buswork. In simulation, the improved setup can reach the efficiency of about 15%, which is about 2 times of the present result.

V. CONCLUSION

Launcher operation has been demonstrated to 140 m/s with a mass of 360g, but an efficiency of only 7%. Measurement and analysis has determined the loss is dominated by skin-current resistances, distributed throughout the circuit. Simulation of the circuit with practical improvements in the configuration of the conductors, surface area and cross-section, indicate that an efficiency of 15% could be obtained.

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